THE RELEVANCE TODAY OF WOLFGANG VON KEMPELEN'S 'SPEAKING MACHINE'

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Abstract

Scientific interest in von Kempelen's 'speaking machine' stems mainly from a general interest in the history of science. This study, however, is devoted to the question of what relevance the 'speaking machine' has today. Apart for discussing why it fascinates researchers and non-researchers alike we describe the construction of a replica and its potential as an instrument for demonstration and for researching speech generation.

Zusammenfassung

Die wissenschaftliche Beschäftigung mit der Kempelen'schen Sprechmaschine erfolgt zumeist aus wissenschaftshistorischen Motiven heraus. Der vorliegende Aufsatz widmet sich der Frage, welche Bedeutung der Sprechmaschine heutzutage zukommt. Neben möglichen Erklärungen, weswegen die Sprechmaschine auf Wissenschaftler wie Nicht-Wissenschaftler faszinierend wirkt, beschreiben wir den Einsatz von Nachbauten als Instrument zur Demonstration und auch zur Erforschung der Erzeugung von Sprachschall.

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1. Introduction

Wolfgang von Kempelen's 1791 book "Mechanismus der menschlichen Sprache" ("Mechanism of Human Speech and Language") and the description of his 'speaking machine' therein have great historical relevance for the phonetic sciences (compare e.g. Dudley & Tarnoczy 1950, Köster 1972, Pompino-Marschall 2004). Various replicas of the 'speaking machine' are witness to its popularity and its unique position in research dedicated to speech generation. Scientific interest in von Kempelen's 'speaking machine' stems mainly from a general interest in the history of science. This study is devoted to the question of what relevance the 'speaking machine' has today.

2. Authenticity

There are no acoustic records to show what von Kempelen's 'speaking machine' sounded like. There are only two more or less reliable sources, both of which indicate what its weaknesses were. On the one hand we have descriptions by contemporaries of Wolfgang von Kempelen who witnessed a demonstration of the 'speaking machine'. On the other hand there are modern replicas which, assuming that they are functioning in the same way as the original, can be made to produce sound.

2.1. Historical descriptions

How did people in von Kempelen's time describe the sound of the machine? The descriptions of their first impression of the machine by two anonymous authors of magazine are quite similar:

> "Hierauf streckte er die rechte Hand durch das große Loch ins Kästgen, drückte mit dem Arme und Ellenbogen den Blasebalg nieder und sprach völlig mit der Stimme eines drey bis vier jährigen Kindes, sehr deutlich und vollkommen gut artikulieret in dem Kästgen aus: 'Oh Maman, Maman, on m'a fait mal!'" (Anonymous 1784a: 180)

> "Then he put his right hand through the big whole into the box, pressed down the bellows with his arm and his elbow and said with the voice of a

> three- or four-year-old child, very clearly and perfectly articulated in the box: 'Oh Maman, Maman, on m'a fait mal!'" (authors' translation)

> "Das erste was wir hörten war: 'Mama, Papa, à (sic) ma chère Mama on m'a fait du mal.' Und nun konnte jeder in der Gesellschaft ein Wort fordern. Alle sprach die Maschine mit der größten Deutlichkeit aus. Auch die doppelten Vocalen und Konsonanten pronunciirt sie sehr rein und richtig. Der Ton ist wie bei einem Kind von drei Jahren. Zuweilen kam das verlangte Wort nicht gleich zum erstenmal richtig heraus, der Künstler mußte verschiedene Versuche machen. Er entschuldigte sich damit, daß einer, der die Violinen macht, sie darum nicht auch fertig spielen könne." [Anonymous 1784b: 483 f.]

> "The first utterance we heard was: 'Mama, Papa, à ma chère Mama on m'a fait du mal.' And then anybody in the audience could request a word. The machine pronounced all words with the greatest precision. Even the double vowels and consonants were spoken very clearly and correctly. The tone is like that of a three-year-old child. Sometimes the requested word was not produced correctly the first time, the artist was forced to make several attempts. He excused himself by remarking that someone who makes violins is not necessarily a virtuoso player." (authors' translation)

There are several other testimonials expressing similar enthusiasm. However, there are also documents by sceptical writers, who considered the speaking machine to be as fake as von Kempelen's chess-playing Turk. For a more detailed treatment of the contemporary reception (inter alia from Goethe) see Brackhane (2009a and this volume).

2.2. The present-day sound

We cannot be sure what the original 'speaking machine' sounded like in von Kempelen day. Was the speech it generated really so natural? Was the sound production really comparable to that of a child? In all probability, the contemporary reports were influenced by several factors. For one thing, in his shows, Kempelen presented the machine immediately after his chess-playing Turk about which the audience was always enthusiastic. Furthermore, as Köster (1972) points out, autosuggestion probably played an important role during the demonstrations: asking the public what they wished to hear informed them in advance what they would hear.

How authentic does the 'speaking machine' sound today? In a different study (Brackhane & Trouvain 2008) we checked this question with unbiased listeners in a perception test, using an open-answer format. The stimuli consisted of everyday sounds and one token of 'Mama' or 'Papa' which were generated with a replica of the 'speaking machine'. The great majority described the sounds as those of a child's voice. For some, the effect was so strong that, after the test, they could not be convinced that it was actually a machine rather than a human child.

Even though the impression of authenticity cannot be maintained for other words, especially for longer utterances, we are able to confirm the observation of the 'speaking machine's' excellent synthesis quality.

3. Simplicity

A more detailed look, and above all *into* the 'speaking machine' tells us that it is a construction which deserves the attribute '(relatively) simple but ingenious'.

3.1. The components

Table 1 lists the components of the speaking machine. The material used to build the different components (cp. also Figure 1) are wood, leather, rubber and metal as well as ivory and glue in order. Each component corresponds to some part of the anatomy of the human speech production system although the anatomical correspondence is far from correct. For example the nostrils are located directly after the glottis. Similarly, the fricative generators are placed directly after the trachea.

Table 1. The components of the 'speaking machine'. Please note that the block, the reed 'tongue' and the shallot are named 'lingual pipe' in organ building.

Analogon	Component	Material
lungs	bellows + frame	wood, leather, lead (weight)
trachea	wind box	wood, screws, cupper (tube)
larynx	cylindric block	wood
vocal folds/glottis	reed + shallot	wood, leather, glue, ivory
nasal cavity	round slice + nostril tubes	wood, brass
vocal tract	funnel	rubber
friction	mouthpieces of recorders	wood, brass (lever)

3.2. The inner life of the actual 'speaking machine'

Although the 'speaking machine' is usually shown in its resonance box linked by a tube to the bellows this hollow body only has a small acoustic effect. The actual generation of speech takes place inside this bigger box. In Figure 1 the central components listed in Table 1 can be compared with Kempelen's original drawing and the Saarbrücken replica.

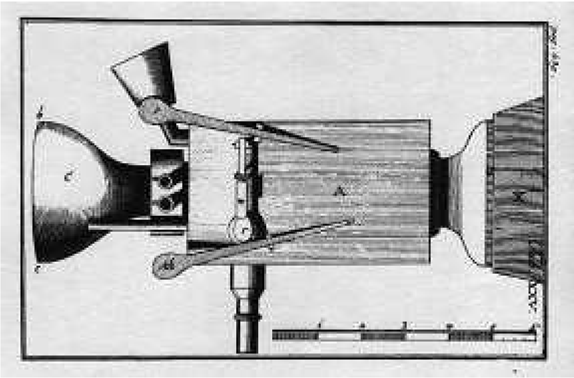

Figure 1. Left: The inner life of the speaking machine shown in the original drawing by von Kempelen (1791). Right: One of the replicas built in Saarbrücken.

3.3. The 'speaking machine' as a musical instrument

The 'speaking machine' could be regarded as a musical instrument, not least because a reed is used to excite the air, just as it is in organ building. Also, as with any instrument, the person using it needs a certain amount of practice to gain the necessary motor skills.

The skill of playing the 'speaking machine' can be compared with articulatory synthesis (e.g. Kröger & Birkholz 2009) and the analysis of speech gestures underlying it. The articulatory plan in Figure 2 can be regarded as a sort of score which the 'speaking- machine' player executes by making hand and arm gestures – in contrast to a human speaker who executes gestures with her/his lips, tongue, velum and vocal folds. For the following example the selection of parameters is restricted to three:

1. control of the 'sub-glottal' air pressure (using the right elbow "E"),
2. raising the 'velum' (index and ring finger of the right hand "R" cover the 'nostrils'),
3. shaping a closure and graded simulation of the 'tongue' constriction (with the palm of the left hand "L", which covers and gradually uncovers the funnel, to differing degrees).

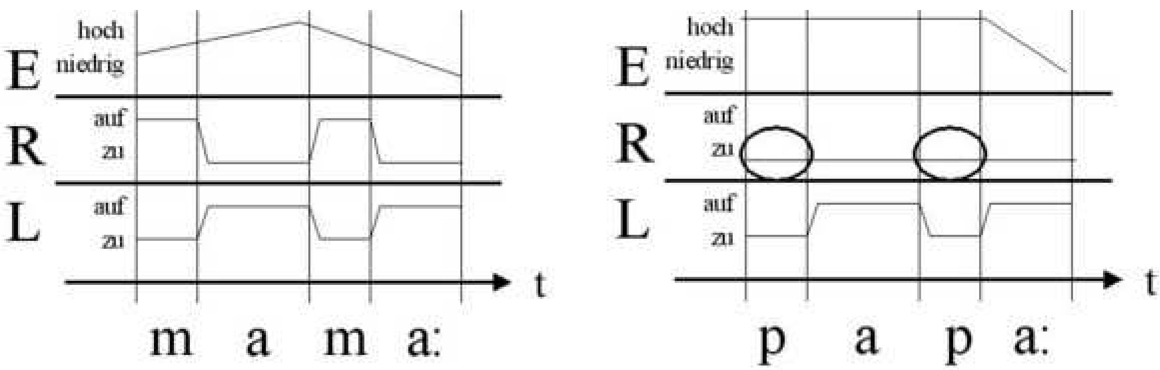

Figure 2. Score of "Mama" and "Papa". E = pressure of right ellbow; R = right hand: index and ring finger cover the 'nostrils'; L = left hand palm simulates degree of 'tongue' constriction by covering and uncovering the funnel, respectively

The main difference between "Mama" and "Papa" lies in the opening and closing of the 'nostrils' during the consonantal articulation, in analogy with the human speech gestures for [m] and [p]. For [p] the velum has to be raised, and the gestures for the machine articulation are the covering of the nasal exit with two fingers of the right hand (see circles for [p] in "Papa" in Figure 2). By stopping the air at the oral and the nasal exit the air flow is suppressed. Usually this initial pressure is responsible for making the so called reed tongue (made from ivory) vibrate as the "vocal fold", without which no tone is generated.

3.4. Reproducability

Recognition, in principle, of the simplicity of the machine's components is possibly what encourages an enthusiast to think "I could build or copy a machine like that".

For many people there is a big difference in the reproducibility of software and hardware solutions. Software-driven technology is not usually reproducible. 'Low tech' (in the best sense of the word) seems to be attractive by the very fact that it *can* be copied, and the haptic sense presumably plays a persuasive role.

However, there are also difficult components such as the bellows – though they can be bought. The modified recorder mouthpieces are optional because they are only used for sibilants. A *real* problem is the production of the 'lingual pipe' ('larynx') which consists of the shallot, the reed and the wooden block surrounding it. From the experience of having built several replicas, the second author can confirm the saying 'the devil is in the detail'.

4. Originals and Replicas

4.1. Original(s)

Even if texts always refer to '*the* speaking machine', the reader should bear in mind that von Kempelen himself experimented with more than just one version of his 'speaking machine' in parallel. For this reason '*the* speaking machine' has never existed, and the historical machine in the Deutsches Museum (Figure 3) cannot be *the* (only) original (Reininger, personal communication) as is so frequently claimed.

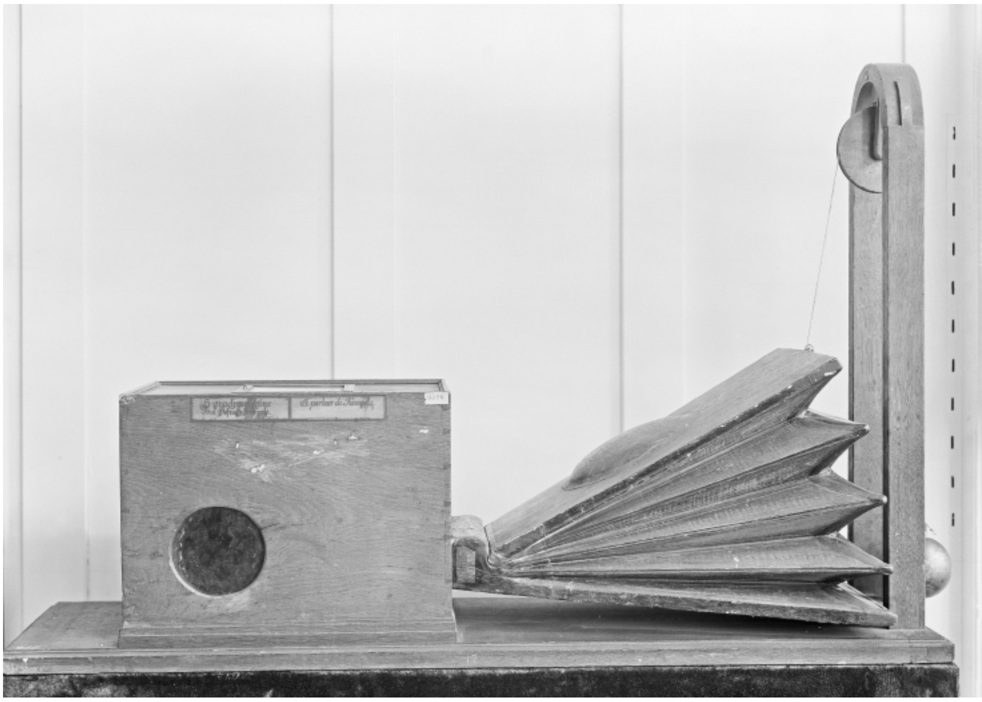

Figure 3. The historical machine in the Deutsches Museum in Munich.

4.2. Replicas

There have been several attempts during the second half of the 20th and the beginning of the 21st century to reconstruct the 'speaking machine' according to the diagrams and descriptions provided in von Kempelen (1791). However, the construction details of the historical model have not been followed to the same degree of fidelity in all cases.

For example the replicas from Vienna (Universität für angewandte Kunst) and England (University of York, Chair of music technology) do without a resonance box and the holding frame which are usually present for demonstrations. For these replicas, the criterion was its playability as an instrument e.g. for performances.

In contrast, both replicas from Budapest (Academy of Sciences) were built with a view to getting as close as possible both in structure and in the acoustic-phonetic details. This also applied to the German replicas constructed in Saarbrücken between 2007 and 2009 (at Saarland University, Chair of Phonetics). Two copies of these are now in Dresden (Technical University, Chair of Communicational Acoustics) and in Paderborn (Heinz Nixdorf MuseumsForum).

This list only serves to illustrate the variability from one replica to another. It is definitively not a complete list because it can be assumed that there are currently a good dozen (partially) functioning replicas in Europe (cp. Brackhane 2009a).

5. The 'Speaking Machine' as an Instrument for Demonstration

The 'speaking machine' has always been found to be an extra-ordinary and convincing instrument for demonstrations. This is true for the European courts in von Kempelen's time as well as for today's classrooms. An instrument just consisting of wood, metal, leather, rubber and a bit of ivory has a fascinating effect despite, or perhaps because of the electronic methods of generating speech that have been in use now for several decades.

Even if we have attempted to explain the fascination with the 'speaking machine' in the previous sections by pointing out its authenticity and simplicity as well as its reproducibility, it is important to identify the people who are attracted to it, what they find attractive and what their scientific interests are.

After many performances with the Saarbrücken replicas in front of very different audiences – even if the speech was usually only 'Mama' and 'Papa' – we can report that nobody was left unimpressed. This is true for students as it is for professors, for children as well as for older persons, for those with a more technical background such as engineers as well as for those with a more human than technical interest such as speech pathologists. Even those trained in the phonetic sciences are unable to resist the fascination of the 'speaking machine'.

We claim that replicas of the speaking machine can very well serve to illustrate how speech sounds are generated – in more than one modality, in fact, since the user can *see* and *touch* the machine as well as hear it – see also the do-it-yourself vowel resonators in Huckvale (2008). Experiencing and understanding in multiple modalities provide an outstanding and a rather unusual opportunity to observe the process of speaking, which is mostly invisible, unconscious and obscured by the focus on the content of what is said. One interesting aspect of demonstrations is the fact that the player of the instrument feels impelled to silently articulate in synchrony with the 'manual articulation'. Apparently it is easier for the player to articulate manually when the cognitive control of the speech articulators takes place. Possibly this 'inner speech' can be suppressed only by a conscious effort. A side effect is that the spectator has the impression that the player is articulating with the voice of the machine.

Ultimately, experiencing the 'speaking machine' prompts the question 'How can it be that this construction of wood, leather and metal can speak like a human being?', and that question inevitably leads to the core of the phonetic sciences: 'How is it that humans are able to speak?'.

Von Kempelen too started in the 18th century with this problem. He was fully aware of the limitations to the practical application of his research. He finished his chief work (Kempelen 1791) inter alia with the wish that his readers "give some attention to this new invention, which is still in its infancy, and that they advance it by their thinking and effort."

6. The 'Speaking Machine' as an Instrument for Research

In our view, the significance of the 'speaking machine' goes beyond that of a unique instrument for demonstrating the generation of speech. A convincing voice quality is dependent on the correct initial air-flow on an appropriate material which starts to vibrate. In terms of the human voice apparatus, we have in the machine something more like a unilaterally paralysed vocal fold, where there is no control over either adduction or abduction and where no change in the shape of the vocal fold is possible. In this respect, these experiments on phonation are closer to those using larynges removed from cadavers (e.g. Alipour & Jaiswal, 2008) than the modelling of phonatory processes in vivo.

6.1. Role of the sub-glottal resonance cavity

We performed tests with wind boxes of different sizes linking the 'lingual pipe' as the phonatory element and the bellows as the 'lung'. It has been shown that the size of the wind box as the 'sub-glottal' resonant cavity has a great impact on the degree of authenticity of the artificial children's voice (Brackhane & Trouvain, 2008). The results of the authenticity tests are different depending on the size of the box and the type of wood.

So the speech-production question to be answered here is what role the sub-glottal cavity and the generated air pressure play in human speech as well as in the individual character of a person's voice. References to sub-glottal resonance features are not (yet) found in phonetic text books. There is a need for more basic research in this respect (cp. Wokurek & Madsack, 2008).

The question can be extended to voices generated by articulatory synthesis, which often still sound unnatural nowadays. One advantage of experimenting with a replica is the effortless and quick exchange of different 'sub-glottal' cavities.

6.2. Compliance with voiceless stops

One of the prerequisites for phonation is a sufficient transglottal air pressure drop to maintain an airflow. During oral closure, supra-glottal air pressure increases and leads to a reduction of the transglottal air pressure difference – and hence to devoicing. Typically voicing ceases after 15 ms (Ohala & Riordan 1979). The closure phases of fully voiced plosives are usually considerably longer than that and it is assumed that the vocal tract is enlarged in order to maintain a trans-glottal flow and delay the cessation of voicing.

An actively controlled enhancement of the vocal tract can be achieved for example by lowering the larynx or by lowering the tongue body. A passive enlargement of the vocal tract happens through the compliance of tissue (Ohala & Riordan 1979, Ohala 1993). Exactly this effect can be obtained with the speaking machine by means of the 'plosive bellows'. These bellows are located directly beneath the 'nasal cavity' and the two cavities are linked with a small tube (Figure 4).

These second, much smaller bellows also have the effect of lengthening the voiced phase of the plosives. There is evidence of this effect for various replicas. However, replicas *without* these bellows are better at generating voiceless plosives with an aspiration phase before voicing begins. An aspiration effect is not possible in replicas *with* these bellows, where a 'Papa' sounds more like a 'Baba'. The possibility of switching the second bellows on and off would clearly offer a good solution to control the 'areodynamic voicing constraint' (Ohala 1993)

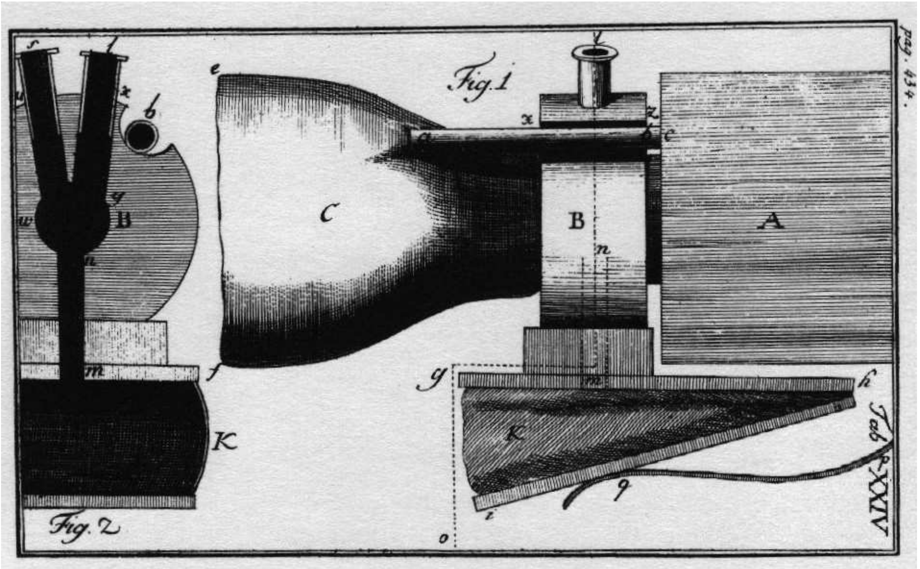

Figure 4. Plosive bellows "K" seen in cross-section in the front view (left-hand side) and in the side view of the inner life of the speaking machine (taken from the original engraving in Kempelen (1791). The 'nasal cavity' ("B") is linked with a small tube ("n") to the plosive bellows located beneath.

It must be noted, however, that it was von Kempelen belief that he was invoking exactly the opposite effect with the installation of the additional bellows:

> "Um die Explosion bey den stummen Mitlautern zu verstärken, habe ich noch einen anderen, nicht minder wichtigen Zusatz gemacht. Ich habe nämlich […] einen kleinen Blasebalg angebracht […]." (Kempelen 1791: 437).
>
> "In order to strengthen the explosion of the unvoiced consonants I have made another equally important addition. I have attached small bellows […]." (author's translation)

In order to obtain a distinction between [b] and [p] with the 'speaking machine', air pressure is increased for [p] compared to [b] immediately before and during the closure of both apertures (also visible in Figure 2). However, the initiation of 'sub-glottal' pressure must not be too strong, otherwise the onset of the 'vocal fold' vibration fails. (Possibly this effect applies to human crying and screaming too, but there it may be offset by adjustment of the vocal fold tension.)

6.3. The prize questions of the St. Petersburg Academy

Further thoughts concern the connection between the generation of human-like voices and organ building as it was stimulated in the prize questions of the academy of sciences in St. Petersburg 1780 under the guidance of Leonhard Euler:

> "1. Qualis sit natura et character sonorum litterarum vocalium a, e, i, o, u tam insigniter inter se diversorum.
>
> 2. Annon construi queant instrumenta ordini tuborum organicorum, sub termino vocis humanae noto, simila, quae litterarum vocalium a, e, i, o, u sonos exprimant." (cp. Kratzenstein, 1781)

> "1. What is the nature and the character of the vowel letters a, e, i, o, u, which so significantly differ from each other.
>
> 2. Is it not possible to build instruments in the manner of those organ pipes which are known under the term 'vox humana' to express the sound of the vowel letters a, e, i, o, u." (authors' translation)

Christian Gottlieb Kratzenstein (1781) won the prize for answering these questions. He provided pipes which generated the requested vowels. Although his approach can be regarded as an important step towards mechanical speech synthesis, those pipes do not show any similarity to vowel production in a human vocal tract. Furthermore, they only generate static, isolated vowels. With the help of a sort of 'organ', an individual key for each single vowel controlled a separate pipe. In contrast, Kempelen took an important step forward. He recognised the central role of coarticulation and built this idea into his machine:

> "Izt fieng ich an einzusehen, daß sich die einzelnen Buchstaben zwar erfinden, aber auf die Art, wie ich es angriff, nimmermehr in Sylben zusammenbinden ließen, und daß ich schlechterdings der Natur folgen müßte, die nur eine Stimmritze, und nur einen Mund hat, zudem alle Laute herausgehen, und eben nur darum sich miteinander verbinden." (Kempelen 1791: 407)

> "Now I started to understand that the single letters could be invented but, in the way I did it, never joined together in syllables, and that I had to follow nature which has only one glottis and only one mouth out of which all sounds are emitted and only for this reason can connect with each other." (authors' translation)

The problem of the second question, asking for the 'vox humana' remains unsolved. The term does not refer to the human voice, as it is sometimes erroneously translated (e.g. Kohler 2000) but the organ register (or 'organ stop') which has existed in organ building for centuries (cp. Brackhane 2009b). This organ register is used with a so called 'tremulant' in order to generate a sound similar to the vibrato of a human singing voice. The 'tremulant' mechanism is located before the pipe and it steers the periodically interrupted air stream to the pipe as the instrument of excitation. A similar mechanism might be used to model machine singing voices, although human singers as well as singing synthesisers modulate glottal parameters to produce vibrato (e.g. Titze 1994, Birkholz 2007).

In the course of his research von Kempelen also took up the idea of using the organ register 'vox humana' as the basis for his speech synthesiser. This is the reason why he used nothing but reed pipes, as in organ building, to act as the vocal folds (with only one vibrating element, similar to a clarinet mouthpiece).

He discarded the construction he had first developed, based on the mouthpiece of an oboe, i.e. with two elements vibrating against each other, similar to human phonation with two vibrating vocal cords. Although he knew of Kratzenstein's work, he did not follow his construction, which was better in some ways (though based on a principle of phonation which was fundamentally wrong). Instead he experimented, among other things, with highly unusual modifications of organ pipes in order to achieve a sound similar to a human voice. A combination of Kratzenstein's reed pipe with von Kempelen's 'speaking machine' would be a very interesting object of research.

7. Speech Synthesis in 18th vs. 21st Century

The 18th century could also be called century of automata, which, of course, included speech automata (Köster 1972). However, the task of these speech automata was the *rendering* of sound. Von Kempelen's invention, on the other hand, dealt with the *generation* of sound. Kempelen's speaking machine was the first ever functioning mechanical speech synthesiser. It is amazing and admirable that the historic speaking machine can stand comparison with the hardware synthesisers of the 21st century (e.g. Fukui et al., 2008). The sound quality is better than that of many modern ones and it is sufficient to authentically mimic a child's voice uttering a two-syllabic word, today as in von Kempelen's time (see section 2).

Interestingly, early mechanical speech synthesisers were also used in the production of toys in the 19th century. A specialisation among the puppet manufacturers was the 'Stimmenmacher, i.e. 'voice manufacturer' (see Hoffmann & Mehnert 2007 for more information on this important historical developments).

Originally the speaking machine was planned as an aid for the deaf. Von Kempelen recognised the strong link between speech and language competence and social acceptance: You are no one unless you can speak. This motivation can also be found for another invention of him when he developed and built a type-setting machine for a blind person (cf. his biography by Reininger 2007).

In the 18th century there was not only a wish to produce synthetic speech per se. There was also a clear idea of what the synthetic voices should sound like. In 1761 Leonhard Euler wrote in his popular scientific 'Letters to a Princess' (Euler 1761):

> "Ce seroit sans doute une plus importantes découvertes, que de construire une machine qui fut propre à exprimer tous les sons de nos paroles avec toutes les articulations. [...] Les prédicateurs & les orateurs, dont la voix n'est pas assés forte ou agréable, pourroient alors jouer leur sermons & discours sur une telle machine, tout de même que les organists jouent des piéces de musique. La chose ne me paroît pas impossible."
>
> "Without doubt it would be one of the most important discoveries to construct a machine that could properly express all sounds and tones of our speech with all articulations. […] The preachers and orators whose voices were not strong or attractive enough could then play their sermons and discourses on such a machine, in the way that the organ players perform their pieces of music. The thing does not seem impossible to me." (authors' translation)

At the beginning of the 21st century, 230 years after von Kempelens invention of the 'speaking machine' we have to face the question, whether the speech synthesisers of today are able to generate sermons and discourses as Euler envisaged. When we consider that the speech synthesis research of the last ten years has taken up topics such as emotions, affect and other forms of non-linguistic expression (cp. Burkhardt & Stegmann 2009), we can at least note some progress. But there is still a massive amount to do before we can give a convincing positive answer of the question. One important step is the acceptance that 'expressing speech with all articulations' means far more than the intelligible transmission of textual information.

8. Conclusion

Even if the importance of von Kempelen's 'speaking machine' mainly lies in the historical dimension, we have to observe that it clearly holds a strong cross-disciplinary fascination for today's researchers concerned with the scientific study of the human voice that it offers a source of inspiration for further research and development of speech- and singing-synthesis.

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